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# P-18 SUSPENSION ROLL STABILITY TEST

JENNIFER KALBERER

LEO DAVIS

AFRL/MLQD
139 BARNES DRIVE, STE 2
TYNDALL AFB FL 32403-5323

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TYNDALL AFB FL 32403-5323





**MATERIALS & MANUFACTURING DIRECTORATE**
**AIR FORCE RESEARCH LABORATORY**
**AIR EXPEDITIONARY FORCES TECHNOLOGIES DIVISION**
**139 BARNES DRIVE, STE 2**
**TYNDALL AFB FL 32403-5323**

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**RICHARD BROWN**
**Program Manager**

**RICHARD N. VICKERS**
**Chief, Deployed Base Systems Branch**

**RANDY L. GROSS, Col, USAF, BSC**
**Chief, Air Expeditionary Forces Technologies Division**

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Tyndall AFB FL 32403-5323

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The Aircraft Rescue and Fire Fighting (ARFF) community and U.S. Military Organizations have experienced several Emergency Response Vehicle rollover induced accidents in recent years. The Air Force has a large inventory of P-18 water tankers (194) and P-19 ARFF vehicles (399) that are subject to rollover incidents. These vehicles are expected to remain in service for at least 15 years. As a near-term solution, retrofitting the suspension system to increase stability may be the only option available at the present time. This report documents the results of testing a P-18 modified with Davis Technologies International (DTI) strut units. Phase I involved testing the P-18 in its current suspension configuration to establish a baseline set of performance data. Phase II involved retrofitting and testing the P-18 with six DTI strut units (one per wheel end). Testing of the P-18 with the DTI suspension system showed that the vehicle could be operated at increased speeds of 10-30% before loss of vehicle control was observed. In most cases, the lateral acceleration required to roll the vehicle was increased to the lateral acceleration at tire slip, so the vehicle was more likely to experience a controlled loss, or slide-out, rather than actual rollover.

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## ABSTRACT

The Aircraft Rescue and Fire Fighting (ARFF) community and U.S Military Organizations have experienced several Emergency Response Vehicle rollover induced accidents in recent years. Rollover accidents have led to serious injury to a number of firefighters, including at least one death, and have caused thousands of dollars in property damage.

The Air Force has a large inventory of P-18 water tankers (194) and P-19 ARFF vehicles (399) that are subject to rollover incidents. These vehicles are expected to remain in service for at least 15 years. As a near-term solution, retrofitting the suspension system to increase stability may be the only option available at the present time. Increasing the roll stiffness of the suspension system will improve the stability of the vehicle, making them less likely to roll during operation. This report documents the results of testing a P-18 tanker truck modified with Davis Technologies International (DTI) strut units. Phase I involved testing the P-18 in its current suspension configuration to establish a baseline set of performance data. Phase II involved retrofitting and testing the P-18 with six DTI strut units (one per wheel end).

Testing of the P-18 with the DTI suspension system showed that the vehicle could be operated at increased speeds of 10-30% before loss of vehicle control was observed. In most cases, the lateral acceleration required to roll the vehicle was increased to the lateral acceleration at tire slip, so the vehicle was more likely to experience a controlled loss, or slide-out, rather than actual rollover.

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## ACKNOWLEDGMENTS

Applied Research Associates, through it's subcontractor, Davis Technologies International (DTI), performed this program for the Air Force Research Laboratory (AFRL), Tyndall AFB, FL under contract number .

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Applied Research Associates of Albuquerque, New Mexico provided project oversight and contract administration.

# SUMMARY

## Introduction

The Aircraft Rescue and Fire Fighting (ARFF) community has experienced several response vehicle rollover events in recent years. Rollover accidents in all branches of the military have led to serious injury to a number of firefighters, including at least one death, and have caused thousands of dollars in property damage. Recent incidents involving a P-18 water tanker at Laughlin AFB, TX and two P-19 ARFF vehicles at Kunsan, Korea and Barksdale AFB, LA have prompted the investigation into upgrading these vehicles for safer operation.

Several factors led to the evaluation of rollover incidents in Emergency Response Vehicles (ERV) in an effort to make them safer including the center of gravity of the vehicle, response time constraints and future changes in regulation.

The Air Force has 194 P-18s and 399 P-19s currently in inventory. While the P-19 will be phased out over the next 14-15 years, the P-18 fleet will be in operation for a minimum of 10-15 years. Next-generation vehicles, such as the Colet Jaguar, have features that minimize rollover danger, including an active suspension system that compensates for the high center of gravity and shifting water in the tank. However, these vehicles are expensive and are not entering the fleet in sufficient numbers to replace current vehicles in the immediate future. As a near-term solution, retrofitting of ERVs to increase stability performance while reducing the threat of rollover may be the only option available. This can be accomplished by increasing the roll stiffness of the suspension system, improving stability and making them less likely to roll during operation.

## Scope/Purpose

The technical approach, from a suspension aspect, is to improve roll stability by increasing the roll stiffness of the suspension system in both static and dynamic response forces, increasing the force required to deflect roll angle from the body to the axle in dynamic-operation. Therefore, the lateral shift of the body center of gravity (Cg) is reduced and the moment of Cg to the tire resistance is increased. This means that as lateral forces act dynamically on the vehicle body, the roll speed acceleration can be controlled by increased damping levels, or resistance force added to the spring force. This damping force is added to both the compression, or outside struts, and the extension, or inside struts. The P-18 2000-gallon water tank truck was chosen as the model for this test series due to the large number of vehicles still in operation (194 units) and because this vehicle poses the greatest likelihood of rollover due to it's high Cg.

The test series was divided into two separate phases in order to evaluate the performance of the P-18 with the original suspension system and the Davis Technologies International (DTI) suspension system. Phase I would provide a baseline set of performance data and Phase II would demonstrate changes in vehicle performance as a direct result of the retrofit.

The purpose of the test series was to compare the miles per hour (MPH) and lateral acceleration (lateral G) required to cause the vehicle to roll or slide-out under eight different driving maneuvers to simulate static and dynamic operating conditions before and after retrofit. The static test series gives a comparison to the standard Tilt Table tests normally performed. Each dynamic test series represented a different extreme driving maneuver and provided information based on real-world operations in which rollover is inevitable. The test sequences completed during Phase I and Phase II include constant radius, lane change, slalom, J-turn and J-turn with braking.

**Results**

Each of the five different course configurations showed an improvement in the maximum speed achievable by a P-18 before loss of vehicle control was experienced. J-Turn testing showed the greatest overall improvement in increasing both the MPH (23-30%) and Lateral Acceleration (28-51%) at the point of rollover. Lane Change testing showed an increase in MPH while decreasing the Lateral Acceleration generated at those speeds. In a lane change situation, the P-18 (at the speeds tested) will not experience high enough lateral forces to cause the vehicle roll or lose control due to tire slip. Limitations to the speeds tested were a result of the limited design of the test course rather than the vehicle instability. The Lateral Acceleration necessary to roll the vehicle increased approximately fifty percent (50%) during testing for both the Slalom and J-Turn Right (i.e. 50% more force is required to cause the vehicle to roll). Similar significant increases (>25%) in Lateral Acceleration generated before loss of control were also recorded for the Constant Radius and J-Turn Left testing.

Modification of the P-18 with the DTI struts increased the lateral G required to roll the vehicle close to that required to cause tire slip, affecting the steering response of the vehicle and giving the driver a physical warning prior to rollover. In many standard operations, the driver has no physical indication that the vehicle is approaching a high enough lateral acceleration to cause rollover. This is due, in part, to the fact that the lateral G required to roll the vehicle was much lower than the lateral G required to cause tire slip. In situations of tire slip, the steering of the vehicle was affected and the driver was given a physical warning (i.e. vehicle slide, sudden tugging in the steering wheel) that the vehicle was losing tire adhesion and that slide-out or rollover were eminent.

**Conclusions**

1. **Vehicle Speed.** The original operating speed of the vehicle before retrofit was between 25-37 miles per hour. After retrofit with the DTI suspension system, vehicle operation speed was increased by as much as 30%. While increased operational speed was not considered the most important outcome of the retrofit, any increase in speed would theoretically result in a shortened response time.

2. **Vehicle Response and Control.** The driver noted an increase in vehicle response and handling after retrofit. The lateral force required to roll the vehicle approached that which would cause tire slip. This provided the driver with a physical response indicating that the vehicle was approaching the limits of safe operation.

3. **Vehicle Stability.** Vehicle stability is the key issue in the safe operation of the P-18. Retrofit with the DTI suspension system increased vehicle stability significantly (i.e. 50% in some cases). In all eight tests, the retrofitted vehicle demonstrated stability at speeds that would have caused the original vehicle to slide-out or roll; further testing performed at increasing speeds showed similar stability.

**Recommendations**

The following modifications are recommended in addition to retrofitting with the DTI suspension system:

1. **Speed Notification Device.** An audible (i.e. verbal) device or heads-up display on the windshield would relay the speed of the vehicle to the operator without taking attention away from the road.

2. **Governor.** A governor would limit the operating speed of the vehicle and prevent the operator from exceeding the stability limits. Because this vehicle is not a primary firefighting vehicle, a few seconds delay in arrival to the scene will not compromise the capabilities or responsiveness of the firefighters.

3. **Rollover Warning Device.** A device should be installed to warn the operator when the vehicle is approaching the roll angle or lateral force required for rollover or slide-out.

4. **Black Box.** A device similar to an aircraft black box would provide data on the status of the vehicle, as well as, information on the response of the driver throughout the duration of vehicle operation.

5. **Dual Tires on the Rear Axle.** The addition of dual tires on the rear axle of the P-18 would enhance and compliment the stability of the retrofitted vehicle by widening the wheelbase. Changes to the current configuration would include the modification of the tire rim and wheel mounting to accommodate the dual tires and purchase of new tires.

# I. INTRODUCTION

## A. Subject

The Aircraft Rescue and Fire Fighting (ARFF) industry has experienced several response vehicle rollover events in recent years. Rollover accidents in all branches of the military have led to serious injury to a number of firefighters, including at least one death, and have caused thousands of dollars in property damage. Recent incidents involving a P-18 at Laughlin AFB, TX and two P-19s at Kunsan, Korea and Barksdale AFB, LA have prompted the investigation into upgrading these vehicles for safer operation.

Several factors are prompting the evaluation of rollover incidents in Emergency Response Vehicles in an effort to make them safer including:

- **Center of Gravity (Cg)-**Emergency Response Vehicles (ERV), in particular the P-18 and P-19, are prone to rollover during routine operation due to the high Cg and from the shifting weight of water in the trucks.

- **Response time-**Response time is a critical parameter in any emergency operation. Air Force regulations require fire departments to respond to flightline emergency situations in less than three minutes, including donning gear and arriving at the scene. In an effort to arrive quickly on the scene, drivers may compromise the limits of the vehicle in an effort to respond within the designated time period.

- **Changes in regulation-**Changes to the Nation Fire Protection Association (NFPA) Standard 414 may also prompt the necessity to increase vehicle stability. Current NFPA 414 specifications require that ARFF class vehicle demonstrate Side Slope Stability of 26° (Tilt Table angle) and do not require Collision Avoidance testing. Changes have been proposed that would require all ARFF class vehicles to demonstrate Side Slope Stability of at least 30° and to perform a collision avoidance test course without loss of control.

The Air Force has 194 P-18 tanker trucks and 399 P-19 fire trucks currently in inventory. While the P-19 will be phased out over the next 14-15 years, the P-18 fleet will be in operation for a minimum of twenty years. Next-generation vehicles, such as the Colet Jaguar, have features that minimize rollover danger with an active suspension system that compensates for the high center of gravity and shifting water. However, these vehicles are expensive and are not entering the fleet in sufficient numbers to replace the P-19 in the immediate future. As a near-term solution, retrofitting of ERVs to increase performance while reducing the threat of rollover is the only option available. Increasing the roll stiffness of the suspension system will improve the stability of the vehicles, making them less likely roll during operation. The Air Force Research Laboratory at Tyndall AFB, FL (AFRL/MLQC) initiated a research contract with Davis Technologies, Incorporated (DTI) to utilize its suspension technology to develop a cost-effective solution to improve the roll stability of ARFF vehicles. This project will demonstrate proof of concept for future work of this nature.

**B. Scope/Purpose**

The technical approach, from a suspension aspect, is to improve roll stability by increasing the roll stiffness of the suspension system in both static and dynamic response forces, increasing the force required to deflect roll angle from the body to the axle in dynamic-operation. Therefore, the lateral shift of the body center of gravity (Cg) is reduced and the moment of Cg to the tire resistance is increased. This means that as lateral forces act dynamically on the vehicle body, the roll speed acceleration can be controlled by increased damping levels, or resistance force added to the spring force. This damping force is added to both the compression, or outside struts, and the extension, or inside struts. The P-18 2000-gallon water tank truck was chosen as the model for this test series due to the large number of vehicles still in operation (194 units) and because this vehicle poses the greatest likelihood of rollover due to it's high Cg.

The test plan will be divided into two phases of testing:

- Phase I involved testing the P-18 with its current suspension configuration to establish a baseline set of performance data. The vehicle was fitted from the manufacturer with three rigid axles equipped with standard leaf springs on the front and leaf springs over a bogie tandem axle in the rear.
- Phase II involved retrofitting the P-18 with six DTI strut units (one per wheel end) outside the leaf spring sets to provide an adjustable, supplemental spring force that works to augment the spring capacity of the existing leaf springs.

The purpose of the Phase I and Phase II tests was to compare the miles per hour (MPH) and lateral acceleration (lateral G) required to cause the vehicle to roll or slide-out under eight different driving maneuvers before and after retrofit. The static test series gives a comparison to the standard Tilt Table tests normally performed. Each dynamic test series represents a different extreme driving maneuver and provides information based on real-world operations in which rollover is a potential problem. The test sequences completed during Phase I and Phase II include:

- Constant Radius: Left and Right (Static)
- Lane Change (Dynamic)
- Slalom (Dynamic)
- J-Turn: Left and Right (Dynamic)
- J-Turn with Braking: Left and Right (Dynamic)

Table 1 shows the summary of calculations made prior to the Constant Radius test series (static) to estimate the MPH and lateral G required for rollover (Appendix A shows the actual curves generated). These calculations were used as a baseline for both the static and dynamic situations.

**Table 1. Calculated values for speed and lateral acceleration to roll a P-18, 100ft. Constant Radius**

| | Phase I | Phase II | % Change |
|---|---|---|---|
| **MPH** | 26 | 29 | 11.5 |
| **Lateral G** | 0.45 | 0.56 | 26.7 |

## II. METHODS

### A. Specifications and Modifications of the P-18

The P-18 water tanker truck is commonly used by the Air Force as a follow on vehicle to the P-19 fire truck. The weight of the truck is approximately 45,600 pounds including 16691 lbs. (2000 gallons) of water and the vertical and horizontal center of gravity are located at the center of the vehicle and 54 inches from the ground, respectively (Figure 1). Outriggers (Figure 2 & 3), supplied by the Canadian National Research Center (CNRC), were mounted by DTI to vehicle sides at the Dallas/Fort Worth (DFW) Airport test site. The outriggers acted as training wheels to prevent full rollover of the vehicle and provide the test operator with the necessary safety measure to confidently evaluate the handling characteristics as the vehicle reached its dynamic limits, and beyond, to rollover mode. The additional weight of the outriggers was a small percentage of the gross vehicle weight (GVW) of 45,600 lbs. The outriggers weighed approximately 2818 lbs. or 6.2% of GVW.

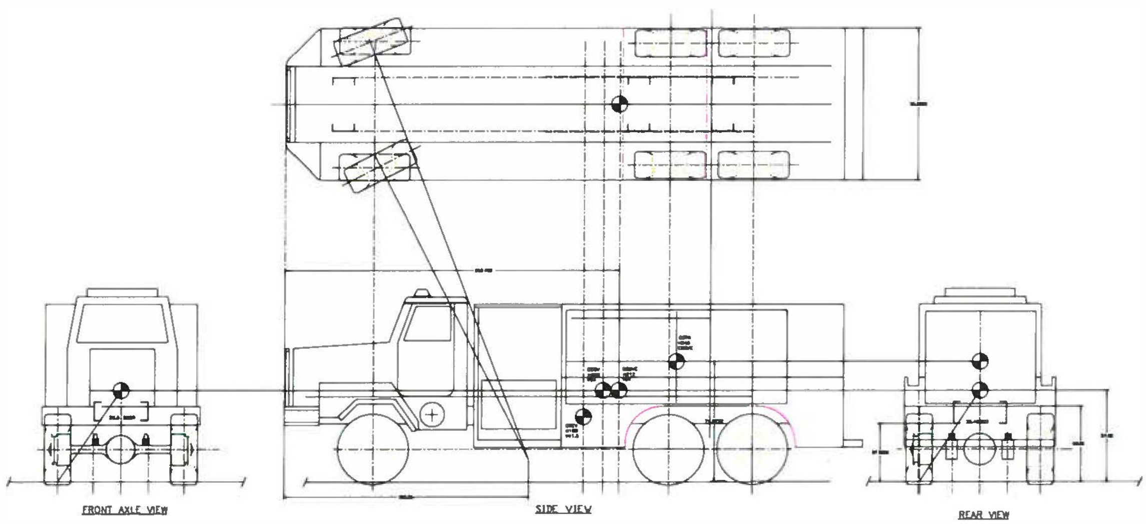


**Figure 1. Truck Specifications for the P-18 Including Center of Gravity**

The outriggers were installed near the horizontal Cg position and about 10 inches below the vertical Cg position to minimize any potential effect they might have on the test evaluation and results.

**Figure 2. Front View: Outriggers Attached to P-18**

**Figure 3. Rear View: Outriggers Attached to P-18**

### B. Data Acquisition and Data Reporting

National Instruments data acquisition equipment was installed on the vehicle to record steering angle, yaw rate, lateral acceleration and vehicle speed (Phase II and Phase I Retest). The vehicle was not fitted with a sensor to monitor vehicle speed in the original Phase I testing, therefore, the most critical tests (Slalom, J-Turn Left and J-Turn Right) were re-evaluated after completion of the Phase II testing and subsequent removal of the DTI struts. Only data collected from those tests will appear in this report. Steering angle and yaw rate were used to pinpoint the moment of rollover and estimate the lateral acceleration experienced at that moment; therefore, only data on Lateral G and speed was included in this report. A complete list of the data acquisition test equipment and sensor/instrument placement on the P-18 appear in Appendix B.

## C. Description of Suspension System and Installation

Six DTI strut units were installed outside the leaf spring sets (Figure 4 & 5). These strut units provide an adjustable, supplemental spring force that works to augment spring capacity of the existing leaf springs. The bi-directional damping function of the strut unit can be tuned to provide different rates of bounce and rebound. The DTI strut's rising rate spring curve is more powerful than the leaf spring curve and can be adjusted to tailor the spring force to control the vehicle more positively throughout the range of suspension motion, increasing roll control as deflection increases. Refer to Figure 28, Appendix A, for a detailed drawing of the Original Equipment Manufacturer (OEM) and DTI suspension systems, including placement of the struts on the P-18.

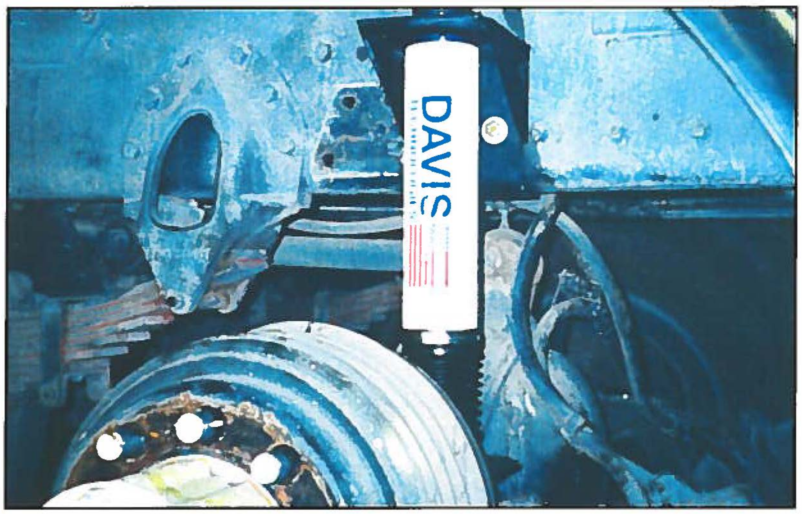


**Figure 4. Installation of DTI Strut Outside Leaf Spring**

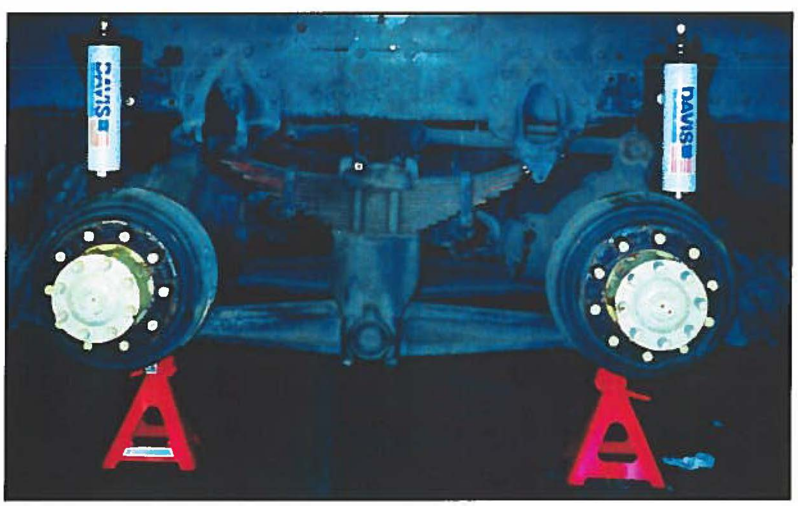


**Figure 5. Installation of DTI Struts on Rear-Dual Axles**

The wheels were removed from each axle to provide room to get into the frame positions to work on the bracket installations. Starting with the rear mounts, the 4 axle stop brackets were removed. The DTI struts replaced the brackets and provided the stop pads limit as well as the spring shock function in the modified configuration. The rear mid axle and the rear axle upper mounting brackets required drilling two additional holes for each of the brackets, using the bracket as a template and then drilling the added holes in the frame web. When this was completed, the rear upper brackets were installed by adding the capscrews, lockwashers and nuts. The lower mounts were located and welded by using a strut assay and a fixture. The struts are common to all six positions and the front installation was complete in a similar approach. Appendix A (Figure 26 & 27) shows a diagram of the location of the original struts and the DTI struts on the P-18, as well as, the roll angle generated by these struts.

**D. Test Methods-General**

The P-18 test procedures followed the Society of Automotive Engineers (SAE) vehicle test procedures.[1-7] Previous testing by the Canadian Transport Research Center (CTRC) on a T-3000 (CTRC) and by the FAA, E-One and DTI on a High Performance Rescue (HPR) Fire Truck were also used in the design of the test series. The matrix of test conditions, courses and test equipment recordings was utilized to investigate the steady state and dynamic state operations to the limits of vehicle control loss and rollover. Phase I and Phase II testing of the P-18 were conducted in Texas at the DWF Airport on a level paved test pad (Figure 6 & 7).

**Figure 6. Phase I Dynamic Testing**

**Figure 7. Phase II Dynamic Testing**

## E. Tilt Table Comparison to Constant Radius Turn

The Tilt Table test is the method most often used by OEM to estimate a static stability limit. This limit relates to the tangent of the table angle in relation to the ground. The Tilt Table test method is intended to determine the static stability limits of the vehicle by simulating the conditions of steady state turning. The angle of the table inclination is slowly increased until the vehicle rolls over. The tangent of the Tilt Table angle is an estimate of the lateral acceleration at which the roll stability of the vehicle is reached. As a comparable substitute, the Constant Radius Turn was used in lieu of the Tilt Table since this equipment was not available. By driving the vehicle in a circle at a constant radius, a static condition can be simulated and a Tilt Table angle can be calculated by taking the cotangent of the Lateral G (Table 2).

**Table 2. Conversion Table of Tilt Table Angle to Lateral G**

| Tilt Table Angle (degrees) | Corresponding Calculated Lateral G |
|---|---|
| 22 | 0.4 |
| 26 | 0.487 |
| 28 | 0.53 |
| 30 | 0.577 |
| 32 | 0.624 |
| 34 | 0.674 |

## III. COURSE AND TEST DESCRIPTION: PHASE I AND PHASE II

### A. Constant Radius Test: Left and Right

In this test, the vehicle is driven around a level 100ft-radius circle in the right and left directions (Figure 8). This test series was used to estimate static rollover conditions, which can be compared to the standard Tilt Table tests. The speed of the vehicle was increased until either lateral G forces caused the vehicle to roll or loss tire adhesion, resulting in a slide-out.

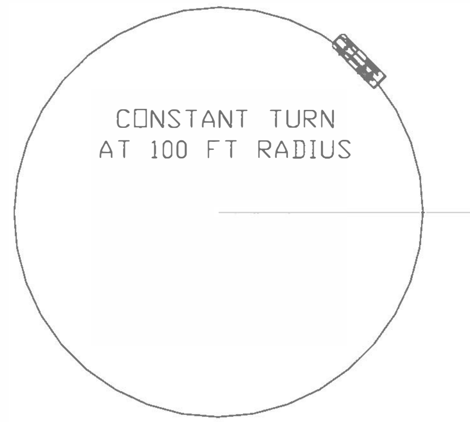


**Figure 8. Diagram of 100ft Radius Course Diagram**

### B. Lane Change

The Lane Change is a dynamic test series that simulates a common vehicle maneuver. The vehicle was driven through a course of traffic cones on level ground as shown in Figure 9. The course included a 50-foot straight approach, a 75-foot transition area (in which the vehicle's path shifted 12 feet to the left side), a 100 foot straight path parallel to the approach path, another 75 foot transition back to the right to the original line of travel and a 50 foot straight departure lane. All straight sections of the course were 12 feet wide. This course was repeated at increasing speeds until the vehicle experienced either roll or slide-out.

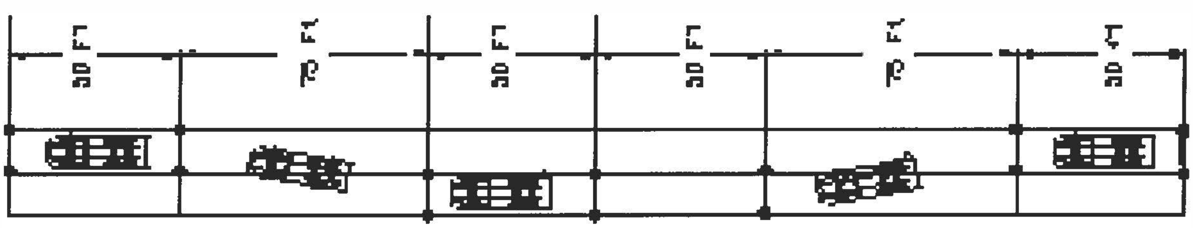

**Figure 9. Lane Change Course Diagram**

### C. Slalom

The Slalom test series is another dynamic test that represents the most extreme driving conditions with small, rapid lane changes (such as those maneuvers encountered in obstacle avoidance). The vehicle was driven through a course of six traffic cones placed in a straight line, evenly spaced at 75 feet (Figure 10). The vehicle approached the first cone offset to the right side at constant speed. Upon approach, the vehicle was turned left after the first cone and then back to the right around the second cone. This path was continued through all six cones, which required three left-hand turns alternated with two right-hand turns. This course was repeated at increasing speeds until the vehicle experienced either roll or slide-out.

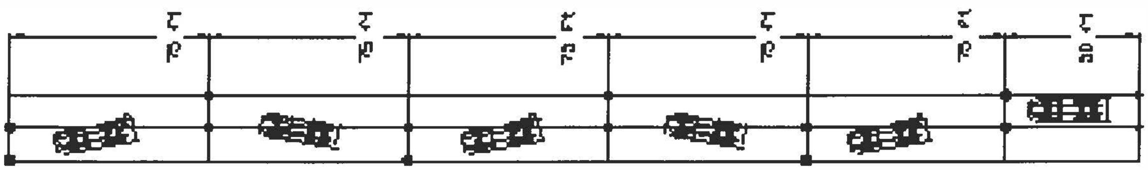

**Figure 10. Slalom Course**

### D. J-Turn: Left and Right

The J-Turn test series represents extreme cornering at relatively high speeds without braking. The vehicle was driven in a straight line at constant speed then steered into a 90° turn on the corresponding quadrant of the 100-ft radius as shown in Figure 11. This course was repeated at increasing speeds until the vehicle experienced either roll or slide-out.

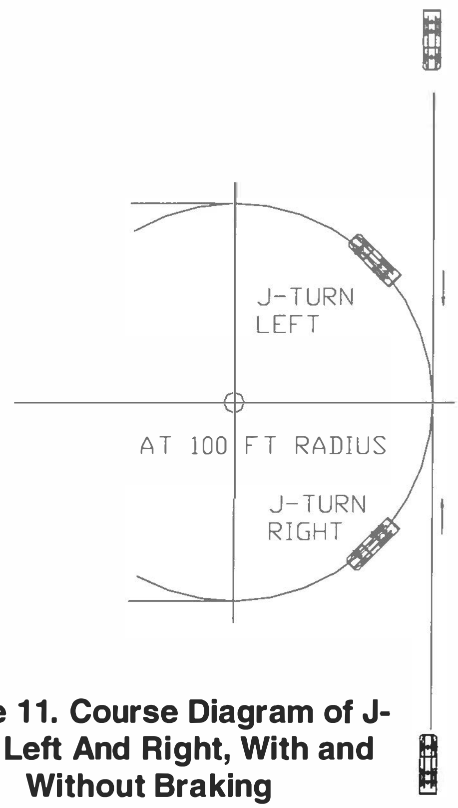


**Figure 11. Course Diagram of J-Turn Left And Right, With and Without Braking**

### E. J-Turn with Braking: Left and Right

The J-Turn with braking test series simulates extreme cornering followed by application of the brakes by the driver as a means to regain vehicle control. Although this test involves several variables, multiple rollover incidents have been attributed to this particular sequence of events, making this test series valuable. As with the standard J-Turn cornering maneuver, the vehicle was driven in a straight line at constant speed, then steered into a 90° turn on the corresponding quadrant of the 100-ft radius. As with the J-Turn test, the vehicle progressed through the arc of the quadrant (turn), however, with this test, hard braking was applied at approximately 45° into the turn.

## IV. TEST RESULTS AND DISCUSSION

### A. Slide-out, Controlled Slide and Rollover (For All Test Sequences) In Relation to Lateral G

As the speed increases, lateral G forces increase and transfer the load to the outside of the tire until the inside wheels of the vehicle lift off the ground, causing the vehicle to roll over. If the lateral adhesion of the tires are exceeded or saturated prior to rollover threshold then tire slip will occur, reducing the lateral force reaction and causing slide-out. If the front tires slip outward prior to the rear tires saturating then a desirable under-steer condition occurs. If both front and rear slide-out simultaneously then a controlled slide occurs, which is preferable to rollover. If the rear tires slide-out first, then an undesirable over-steer and a high rate of yaw occurs, which may cause rollover. If the tires adhere or a curb or soft ground condition is met then rollover is still a potential.

**Note: The number of trials run between Phase I and Phase II may vary within the same test as a result of the number of trials required to reach rollover or slide-out will vary. Trails at speeds beyond those reported in this technical report have been omitted as the report only concentrates on the minimum speed and lateral acceleration required to roll the vehicle. Table 3 lists the MPH and lateral acceleration recorded for each test sequence in Phase I and Phase II.**

Table 3. MPH and Lateral Acceleration for Phase I and Phase II Testing

| | Phase I | | | Phase II | | |
|---|---|---|---|---|---|---|
| **Test** | **MPH** | **Lateral G** | | **MPH** | **Lateral G** | |
| | | Left | Right | | Left | Right |
| **Constant Radius** | | | | | | |
| • Left | 20 | | 0.36 | | | |
| | 22 | | 0.41 | | | |
| | 24 | | 0.43 | | | |
| | 25 | | 0.47 | | | |
| | 26* | | 0.52 | 29* | | 0.65 |
| • Right | 20 | 0.37 | | | | |
| | 22 | 0.43 | | | | |
| | 24 | 0.46 | | | | |
| | 26* | 0.48 | | 30* | 0.63 | |
| **Lane Change** | 26 | 0.37 | 0.35 | 30 | 0.32 | 0.32 |
| | 28 | 0.32 | 0.31 | 36 | 0.37 | 0.43 |
| | 30 | 0.39 | 0.415 | 39 | 0.37 | 0.45 |
| | 33 | 0.38 | 0.49 | 41 | 0.32 | 0.42 |
| | 35 | 0.35 | 0.56 | 41 | 0.36 | 0.48 |
| | 37** | 0.4 | 0.53 | | | |
| **Slalom** | 25 | 0.39 | 0.44 | 28 | 0.5 | 0.5 |
| | 27 | 0.44 | 0.47 | 31 | 0.57 | 0.57 |
| | 27 | 0.55 | 0.51 | 31 | 0.60 | 0.51 |
| | 28 | 0.52 | 0.51 | 32 | 0.66 | 0.66 |
| | 30* | 0.53 | 0.63 | 32 | 0.61 | 0.57 |
| | | | | 32 | 0.69 | 0.57 |
| | | | | 32 | 0.55 | 0.57 |
| | | | | 32 | 0.57 | 0.57 |
| | | | | 33 | 0.84 | 0.62 |
| | | | | 33 | 0.76 | 0.63 |
| | | | | 34 | 0.72 | 0.67 |
| | | | | 35* | 0.74 | 0.70 |
| | | | | 35* | 0.79 | 0.62 |
| | | | | 35* | 0.80 | 0.70 |

* Tip
** Slide
*** Slide and Tip

Table 3. Continued

| | Phase I | | | Phase II | | |
|---|---|---|---|---|---|---|
| **Test** | **MPH** | **Lateral G** | | **MPH** | **Lateral G** | |
| | | Left | Right | | Left | Right |
| **J-Turn** | | | | | | |
| • Left | 23 | | 0.41 | 28 | | 0.61 |
| | 25 | | 0.48 | 30 | | 0.64 |
| | 26 | | 0.49 | 32 | | 0.67 |
| | 26 | | 0.54 | 32* | | 0.76 |
| | 26* | | 0.65 | | | |
| • Right | 24 | 0.45 | | 25 | 0.45 | |
| | 25* | 0.49 | | 28 | 0.59 | |
| | | | | 31 | 067 | |
| | | | | 31 | 0.70 | |
| | | | | 31 | 0.67 | |
| | | | | 31 | 0.62 | |
| | | | | 32 | 0.67 | |
| | | | | 32.5* | 0.74 | |
| **J-Turn w/Brake** | | | | | | |
| • Left | 25 | | 0.44 | 27 | | 0.47 |
| | 26 | | 0.51 | 29 | | 0.58 |
| | 28*** | | 0.58 | 31** | | 0.63 |
| • Right | 24 | 0.53 | | 26 | 0.48 | |
| | 26*** | 0.63 | | 29 | 0.47 | |
| | | | | 30 | 0.52 | |
| | | | | 31 | 0.67 | |
| | | | | 31** | 0.62 | |

* Tip
** Slide
*** Slide and Tip

## B. Significance of Lateral G, Tire Adhesion/Slip and Vehicle Control

Control of the vehicle is of utmost importance in the operation of ERVs. In many situations, the driver has no physical indication that the vehicle is approaching a high enough lateral acceleration to cause rollover. This is due, in part, to the fact that the lateral G required to roll the vehicle is much lower than the lateral G required to cause tire slip (Figure 12). In situations of tire slip, the steering of the vehicle is affected and the driver is given a physical warning (i.e. vehicle slide, sudden tugging in the steering wheel) that the vehicle is losing tire adhesion resulting in a controlled slide rather than rollover (although rollover is still a possibility). Modification of the P-18 with the DTI struts increased the lateral G required to roll the vehicle close to that required to cause tire slip, affecting the steering response of the vehicle and giving the driver a physical warning prior to rollover.

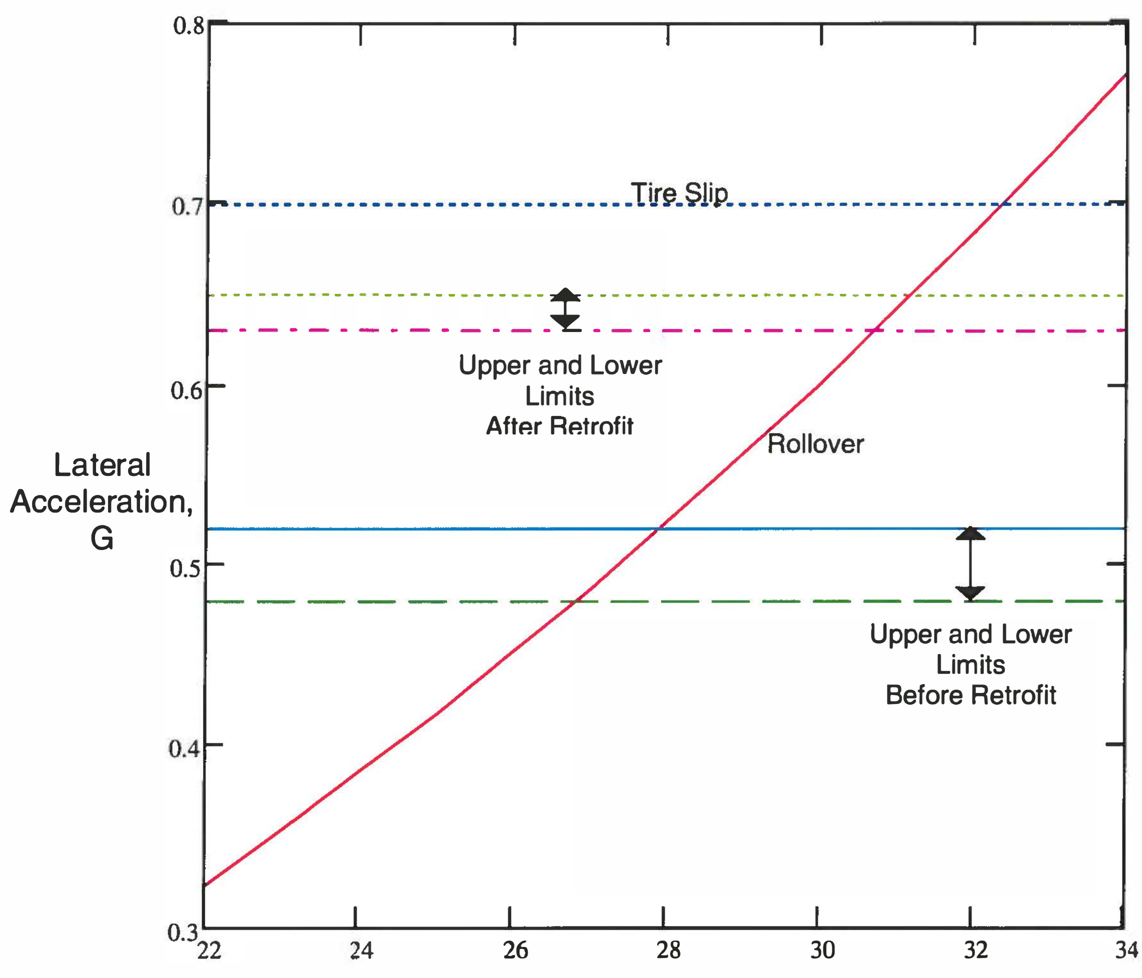


**Figure 12. Tire Slip vs. Rollover Before and After Retrofit From Phase I and Phase II Test Data**

### C. Constant Radius: Left and Right

Phase I Constant Radius Left turn tests showed that the P-18 experienced rollover at 26mph while Phase II tests demonstrated that rollover was not reached until 29mph (Figure 13). The corresponding Lateral Accelerations recorded at the time over rollover were 0.52G and 0.65G, respectively. Due to time constraints, Phase II testing was run as one continuous test, without stopping between changes of speed, resulting in one reading for Lateral G instead of separate records as in Phase I.

Phase I Constant Radius Right turn tests demonstrated that the P-18 experienced rollover at 26mph (Figure 14) while Phase II tests showed rollover occurring at 30mph. Lateral Acceleration recorded at the time of rollover was 0.48G for Phase I and 0.63G for Phase II. As in the Left turn tests, Phase II was conducted as one continuous test due to time constraints.

The Constant Radius test was substituted for the tilt table test and provides an indication of rollover in a static situation (which is not applicable to real life conditions but provides a means of comparison to tests performed in the past). Phase I rollover occurred at 0.52G, which corresponds to a roll angle of 27.5°. Phase II rollover occurred at 0.65G, which corresponds to a roll angle of 33.0°. Results from this test series indicates that retrofit with DTI struts would increase vehicle operation speed to meet or exceed current (22mph) or future (28mph) regulations.

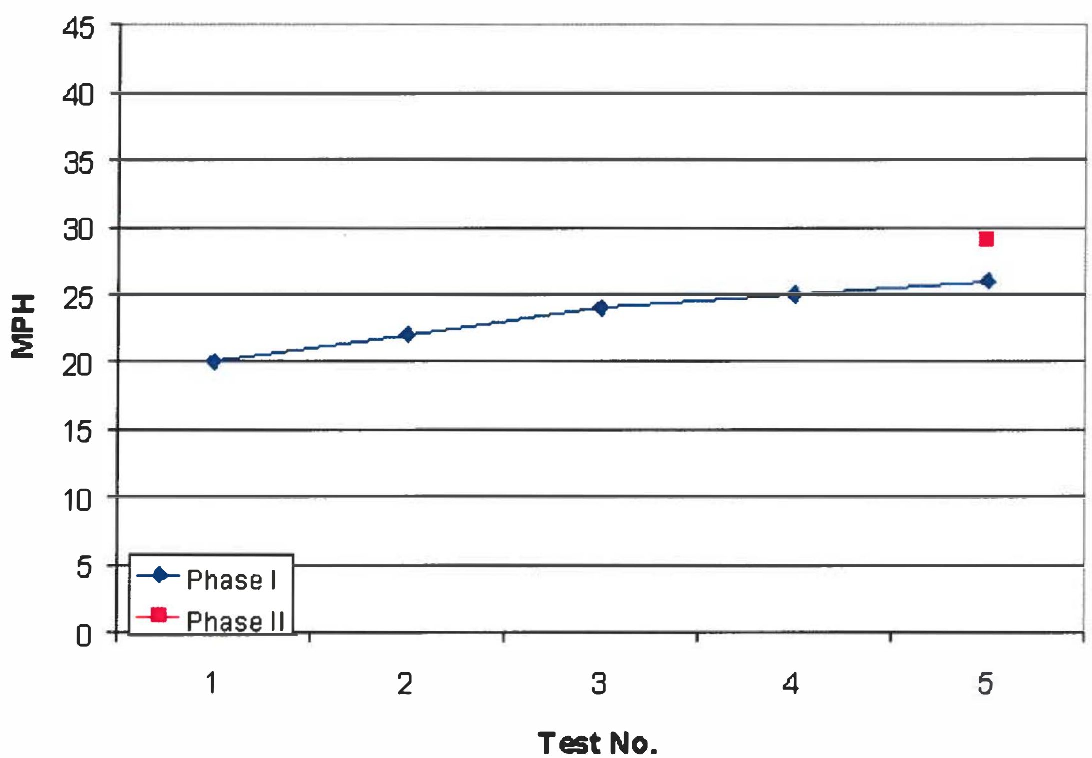


**Figure 13. MPH for 100ft Constant Radius-Left Test Series**

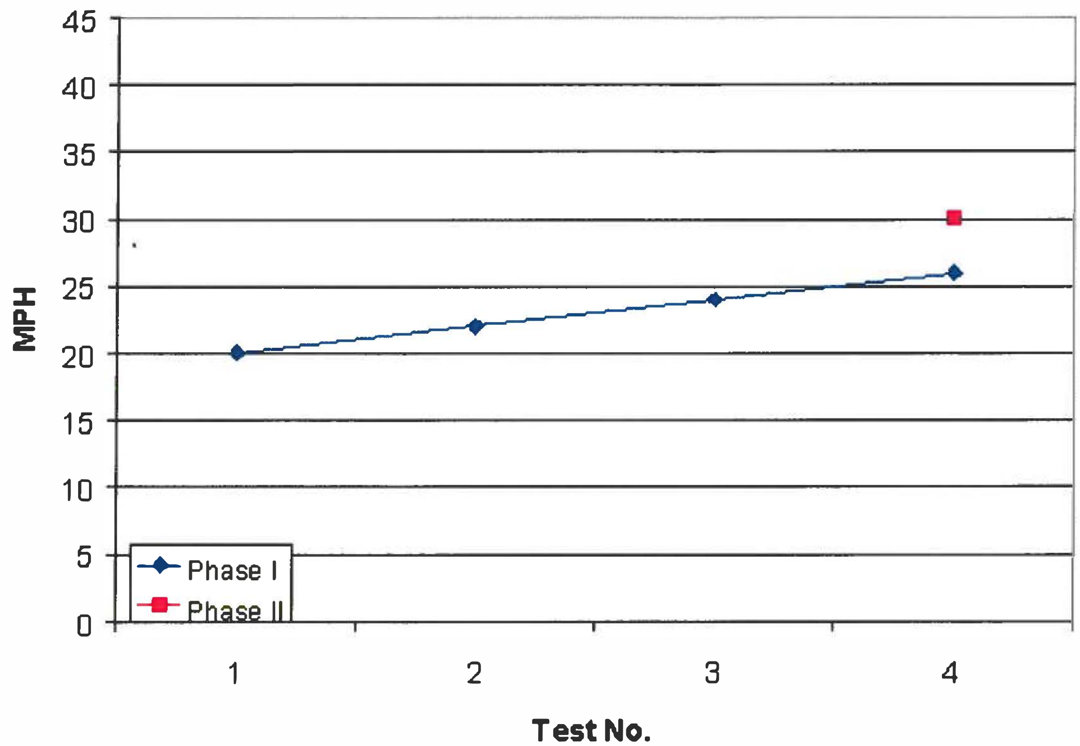


**Figure 14. MPH for 100ft Constant Radius-Right Test Series**

### D. Lane Change

Phase I showed that slide-out occurred at 37mph while in Phase II the vehicle was driven up to speeds of 41mph without rollover, slide-out or loss of vehicle control (Figure 15). The lateral accelerations recorded during Phase I (0.53G) was higher than the average in Phase II (0.45G). This indicates that with retrofitted suspension system, the vehicle was more stable and experienced less tilt at higher speeds. Higher speeds and lateral acceleration could have been achieved during Phase II testing, however, the operator was challenged to accelerate and decelerate in a space-restricted area, thus preventing the vehicle from obtaining higher top speeds that would have otherwise been possible.

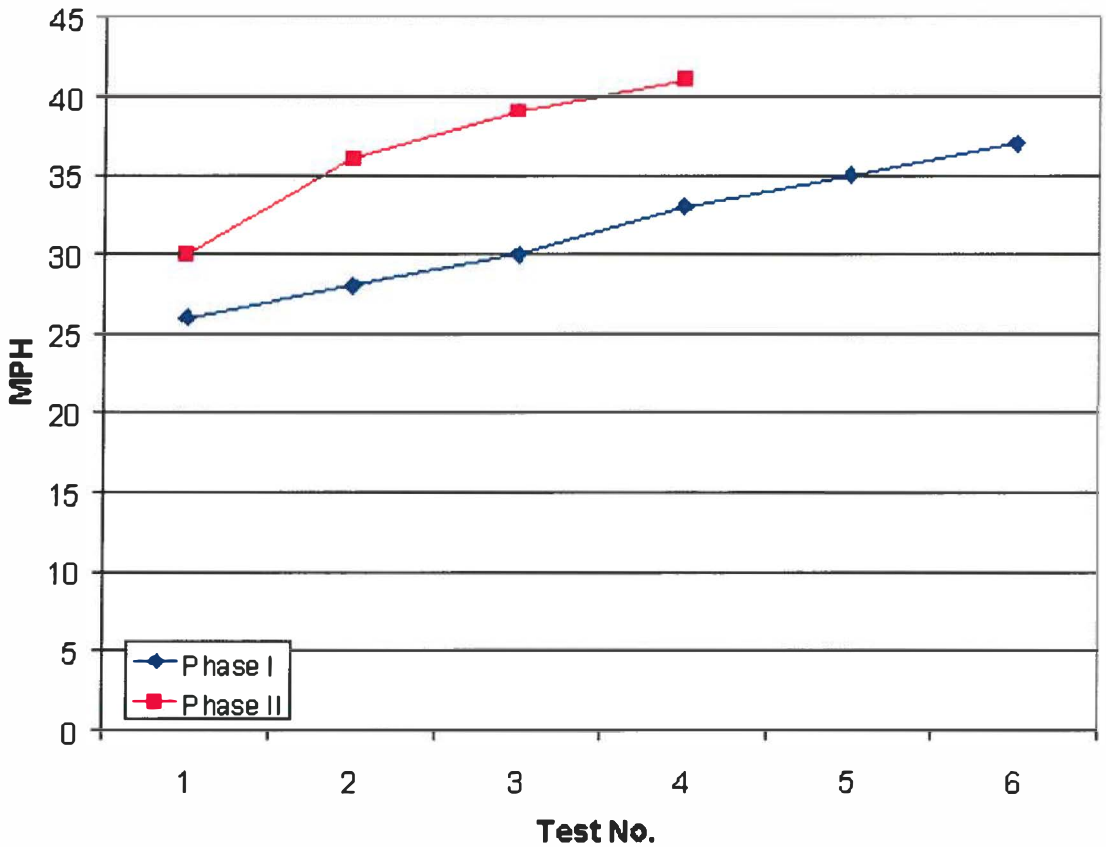


**Figure 15. MPH for Lane Change Test Series**

## E. Slalom

The P-18 experienced rollover at 30mph in Phase I and 35mph in Phase II (Figure 16). The left lateral acceleration at the point of rollover corresponded to 0.53G and 0.78G (average of three trials) for the right steering angle (steering the vehicle in one direction produces lateral acceleration in the opposite direction). Figure 17 shows the lateral acceleration for the Phase I and II trials corresponding to rollover at 0.53G and 0.79G. The retrofit with DTI struts for Phase II testing improved the vehicle response to severe steering inputs by increasing the lateral acceleration necessary to roll the vehicle to the limit necessary to cause tire slip.

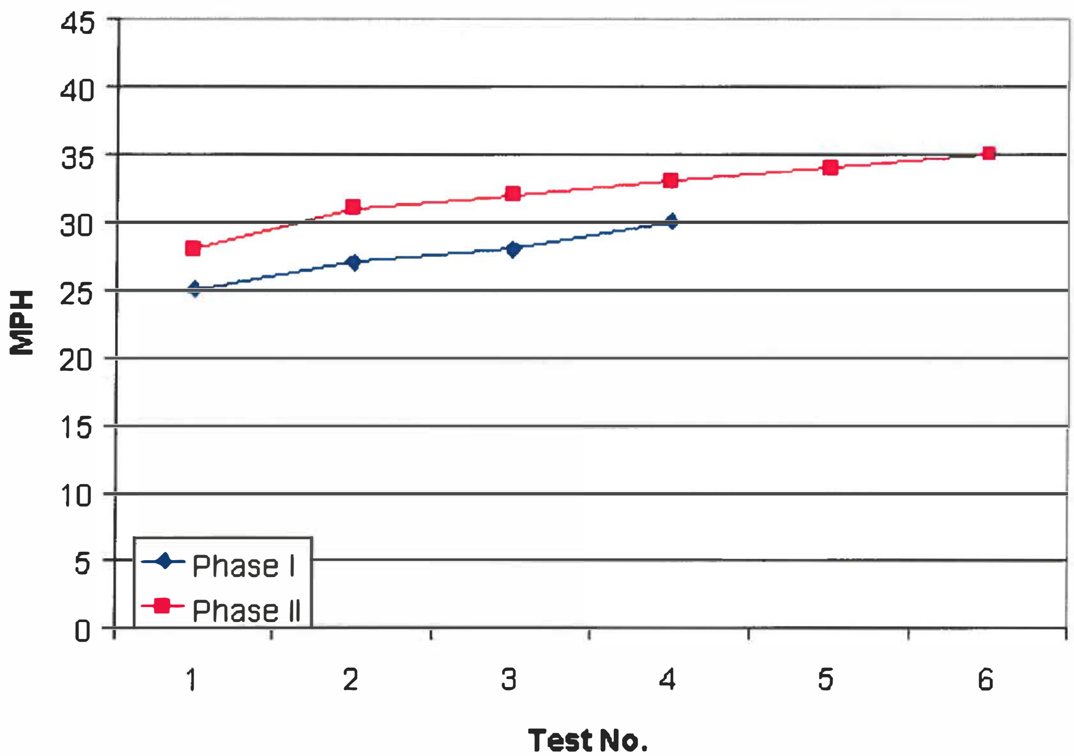


**Figure 16. MPH for Slalom Test Series**

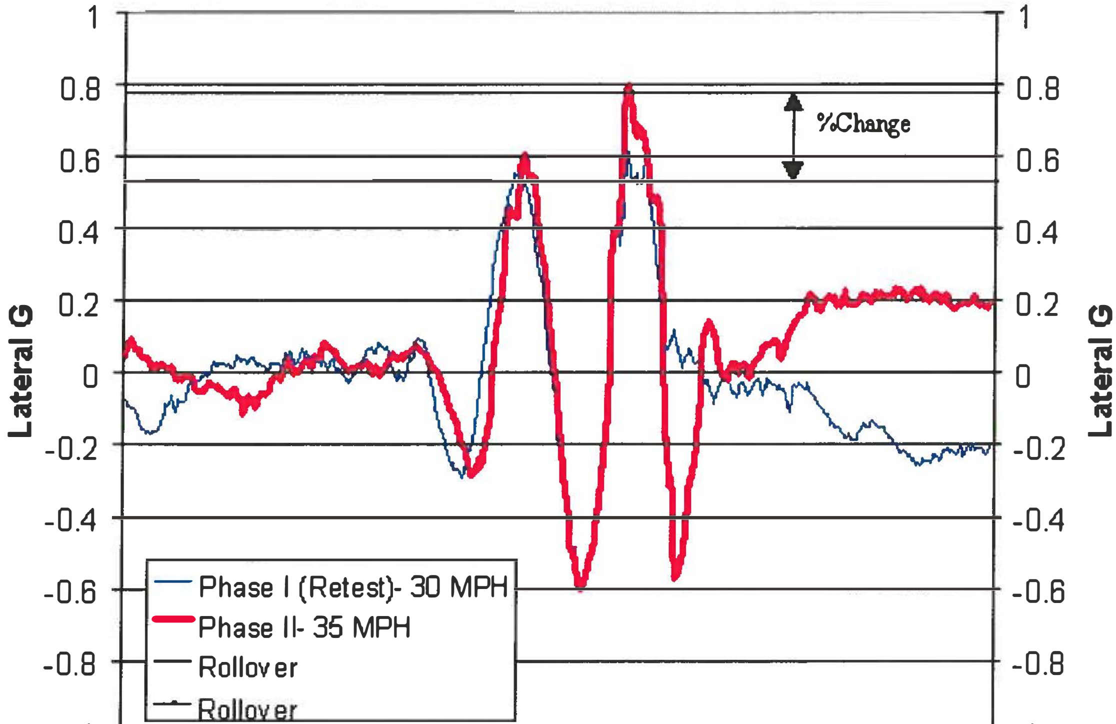


**Figure 17. Slalom Lateral Acceleration Trace**

### F. J-Turn: Left and Right

The P-18 experienced rollover in the J-Turn Left test series at 26mph in Phase I and 32mph after retrofit in Phase II (Figure 18). The average lateral acceleration recorded for this series was 0.56G (Phase I) and 0.72G (Phase II). Figure 19 shows the lateral acceleration trace corresponding to rollover at 0.65G for Phase I and 0.76G for Phase II.

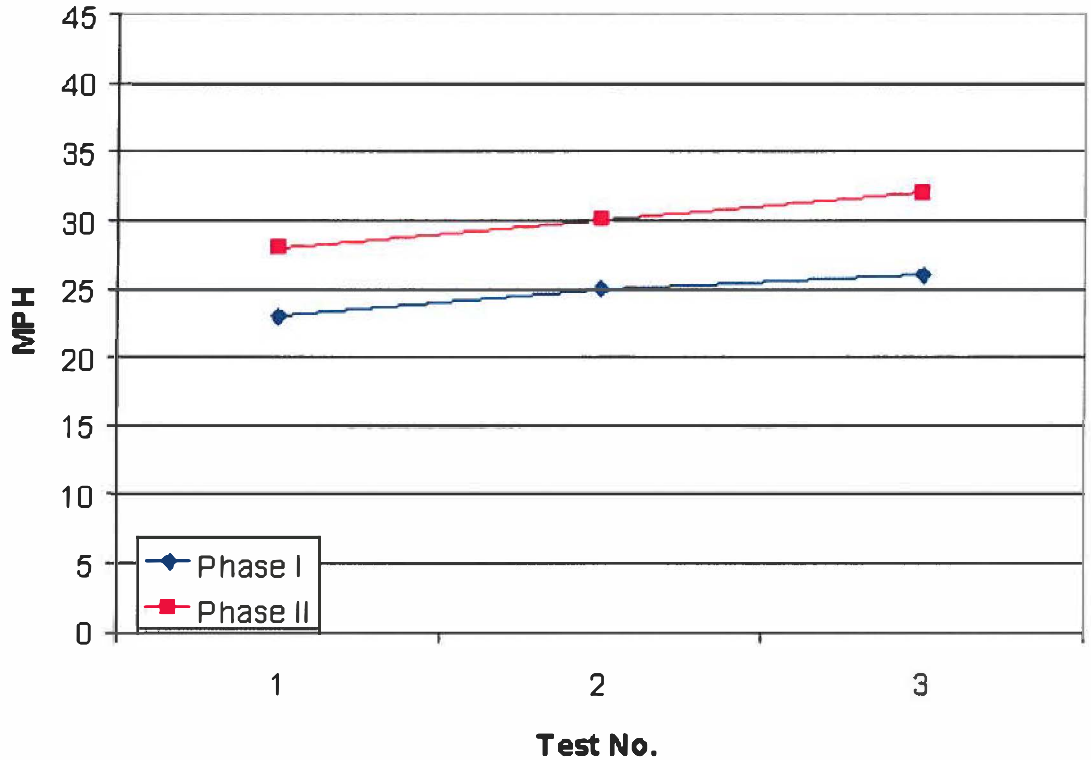


**Figure 18. MPH for J-Turn Left Test Series**

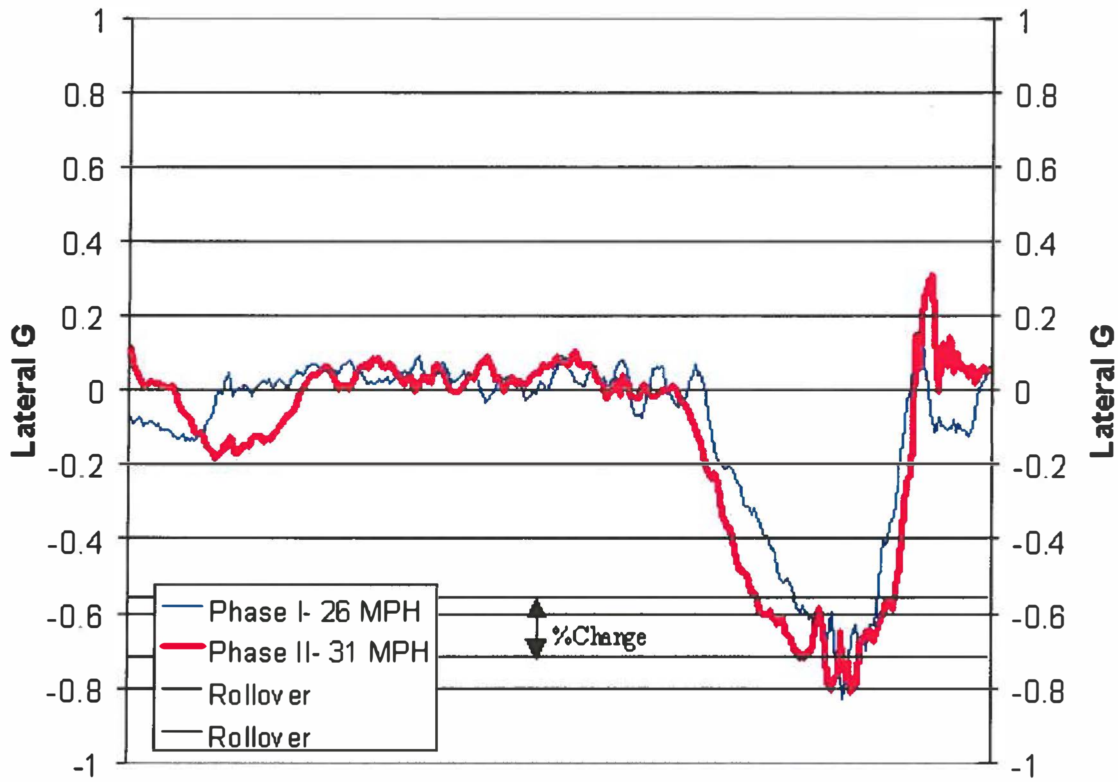


**Figure 19. J-Turn Left Lateral Acceleration Trace**

The J-Turn Right test series yielded similar results to those observed in the J-Turn Left test series. Rollover was experienced in Phase I at 25mph while Phase II testing continued to 32.5mph before rollover was achieved (Figure 20). Figure 21 shows the lateral acceleration recorded at these speeds was 0.49G (Phase I) and 0.74G (Phase II). This type of dynamic stability testing represents the most extreme driving condition. In this situation, vehicle stability is not only going to be governed by the lateral acceleration required to roll the vehicle but also by the tire adhesion limits. Even though the vehicle was made less likely to roll at higher lateral G, the tire adhesion limits remained the same regardless of the suspension system, and loss of vehicle control was still experienced causing rollover.

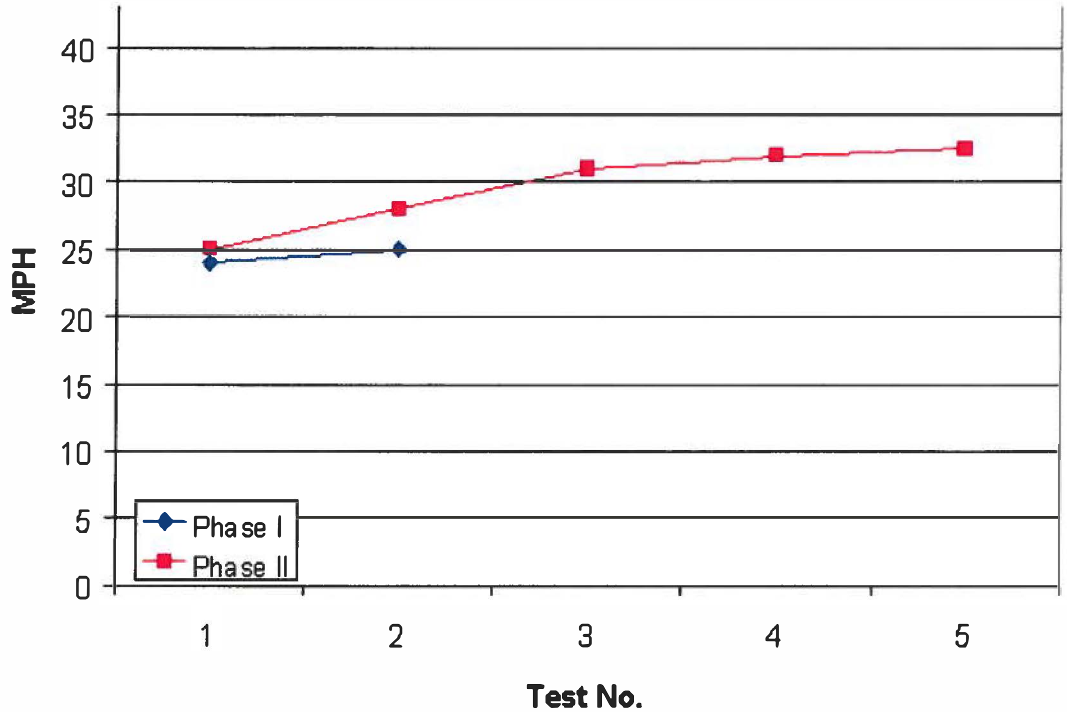


**Figure 20. MPH for J-Turn Right Test Series**

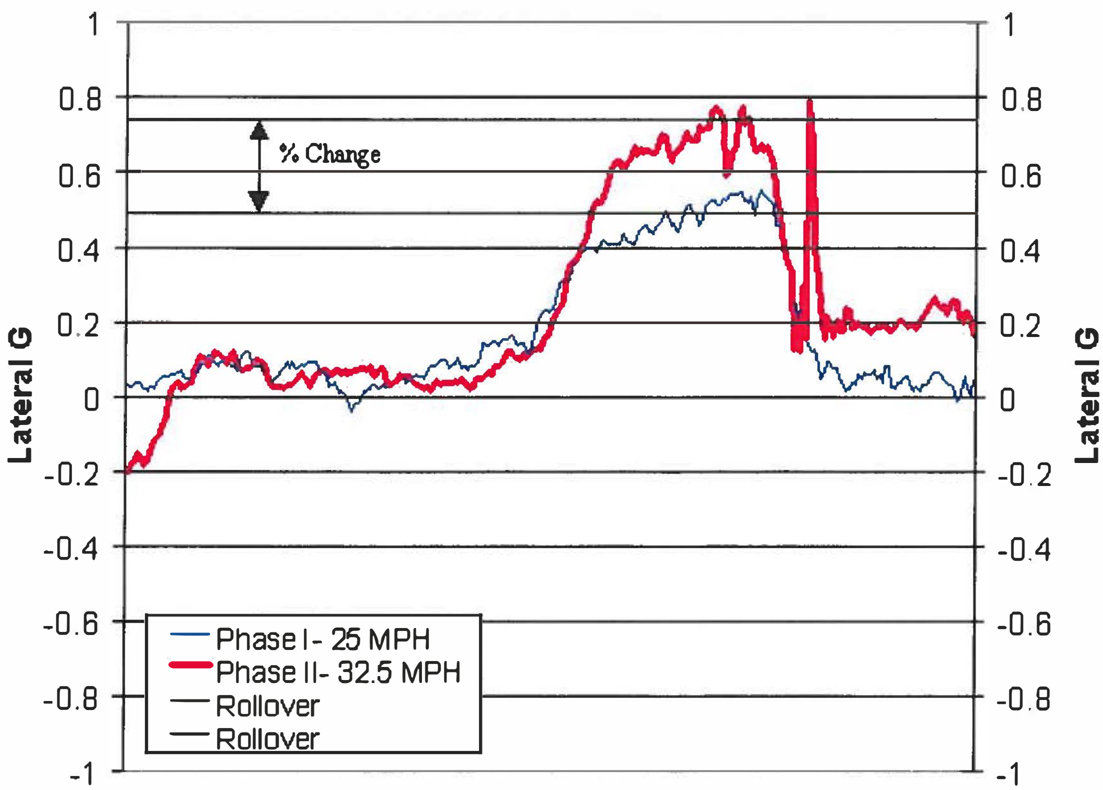


**Figure 21. J-Turn Right Lateral Acceleration Trace**

## F. J-Turn with Braking: Left and Right

The P-18 experienced slide-out followed by rollover in both the J-Turn Left and Right test series. After Phase II retrofit, the same vehicle experienced only slide-out with no subsequent rollover. The speeds associated with these events were 28mph and 31mph for Phase I and II Left and 26mph and 31mph for Phase I and II Right (Figures 22 &24). The lateral acceleration produced in the Phase I Left (0.58G) was lower than that produced in the Phase II testing (0.63G). Phase I Right (0.63) produced slightly lowered lateral acceleration than Phase II (0.645) (Figures 23 & 25). These results indicate that with the retrofit, vehicle speed can be increased without changing the lateral acceleration. Because the lateral acceleration required to roll the vehicle after retrofit was increased to the tire adhesion limit, the vehicle experienced only slide rather than rollover.

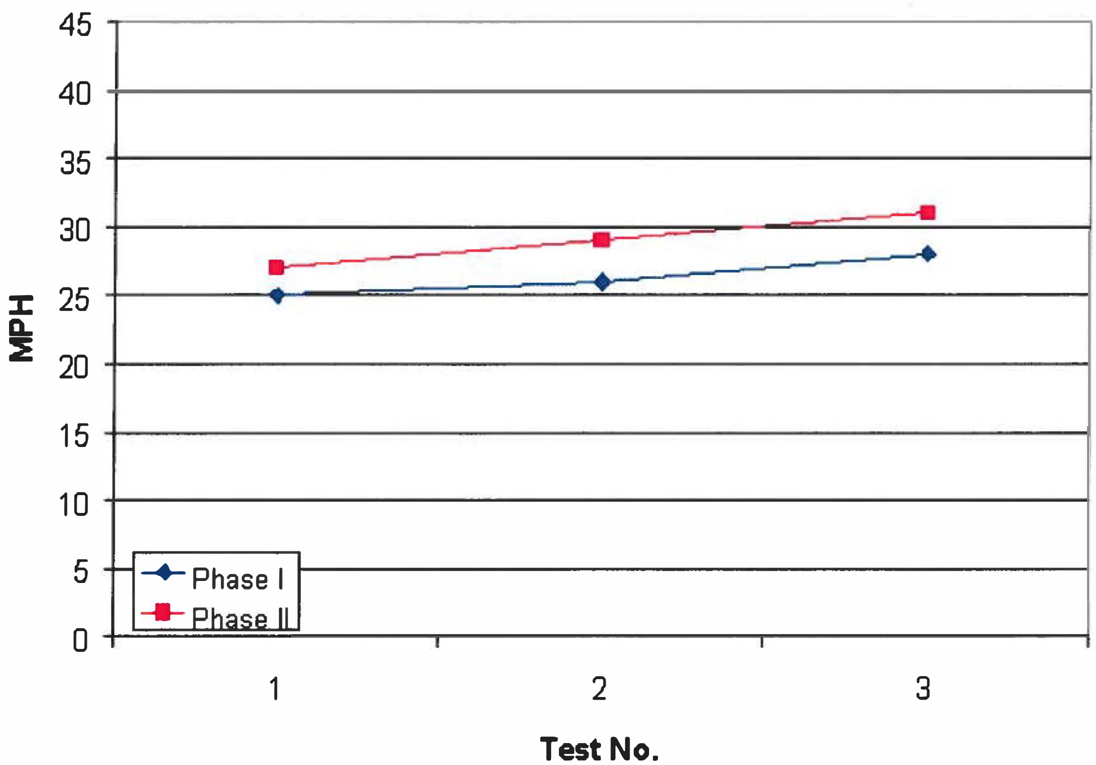


**Figure 22. MPH for J-Turn Left with Braking Test Series**

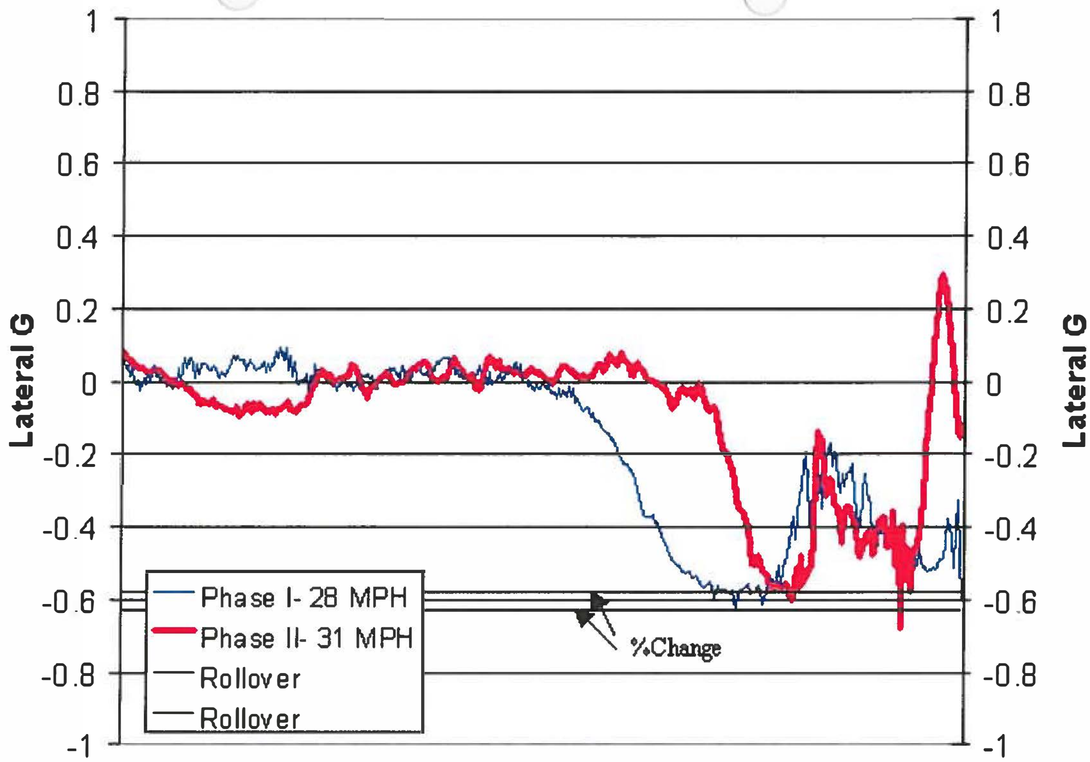


**Figure 23. J-Turn Left with Braking Lateral Acceleration Trace**

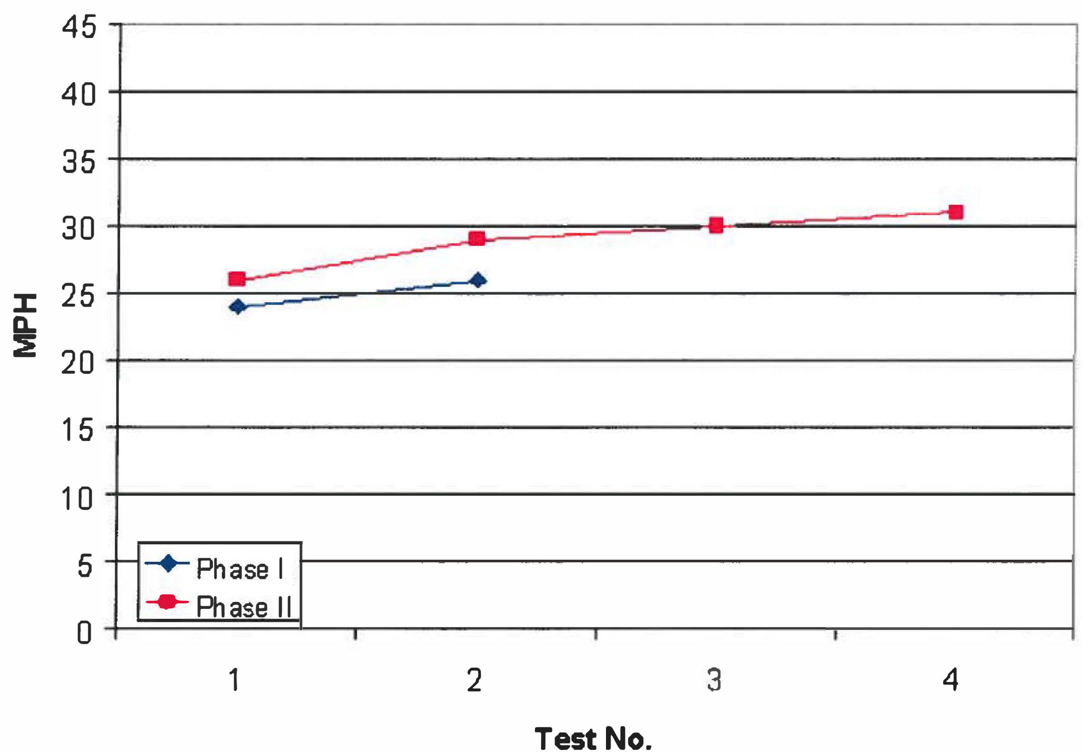


**Figure 24. MPH for J-Turn Right with Braking Test Series**

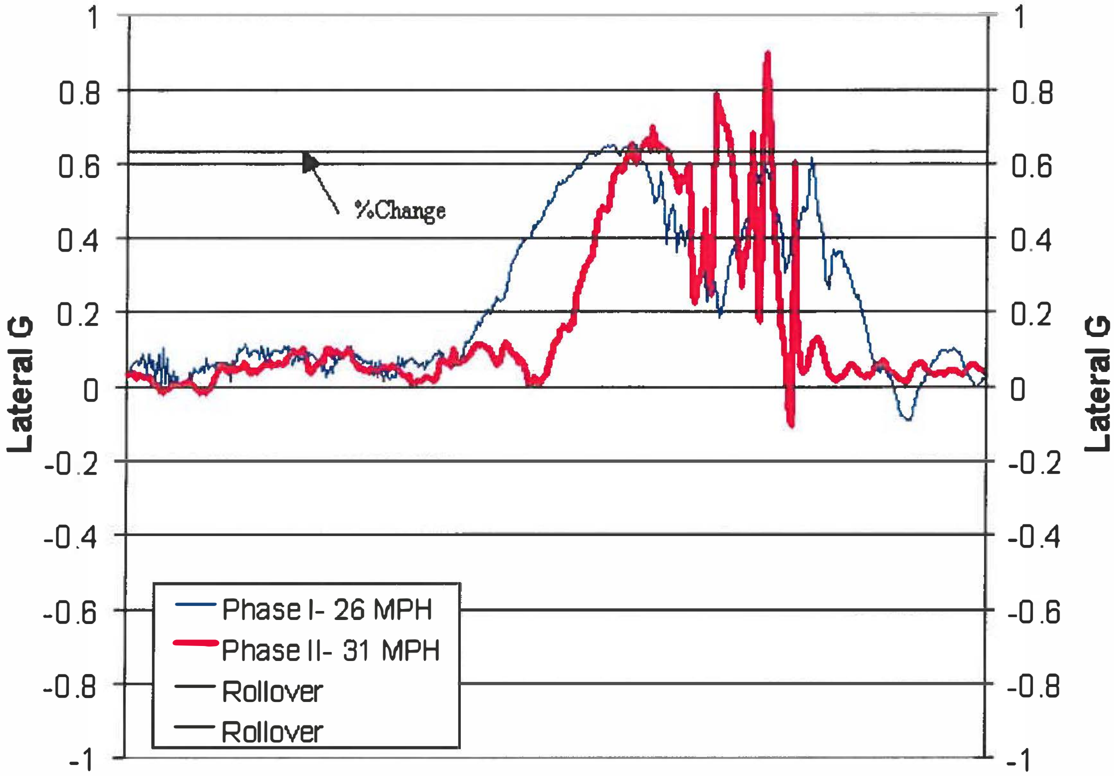


**Figure 25. J-Turn Right with Braking Lateral Acceleration Trace**

In Phase II, the vehicle counteracted roll forces enabling the vehicle to achieve a combination of front and rear wheel slip, which allowed the vehicle to slide to a halt without rollover or loss of driver control. Accidents involving similar driving conditions to those demonstrated in J-turn with braking have been a significant cause of the rollover incidents. Although any loss of vehicle control could lead to a potentially fatal accident, losing tire adhesion, resulting in slide-out, is potentially a better outcome than rolling the vehicle.

## G. Overview of Percent Change

Each of the five different course configurations showed an improvement in the maximum speed achievable by a P-18 before loss of vehicle control was experienced (Table 4). J-Tum testing showed the greatest overall improvement in increasing both the MPH (23-30%) and Lateral Acceleration (28-51%) at the point of rollover. Lane Change testing showed an increase in MPH while decreasing the Lateral Acceleration generated at those speeds. In a lane change situation, the P-18 (at the speeds tested) will not experience high enough lateral forces to cause the vehicle roll or lose control due to tire slip. The Lateral Acceleration necessary to roll the vehicle increased approximately fifty percent (50%) during testing for both the Slalom and J-Tum Right (i.e. 50% more force is required to cause the vehicle to roll). Similar significant increases (>25%) in Lateral Acceleration generated before loss of control were also recorded for the Constant Radius and J-Tum Left testing. The increase in lateral acceleration on the Constant Radius testing was significant enough to meet and exceed the proposed changes to the NFPA 414 Standard for AFRR Vehicles.

**Table 4. Overview of Average Percent Change in MPH and Lateral Acceleration**

| AVERAGE PERCENT CHANGE | | | |
|---|---|---|---|
| TEST | MPH | LATERAL ACCELERATION | |
| | | LEFT | RIGHT |
| Constant Radius | | | |
| • Left | 11.5% | | 25.0% |
| • Right | 15.4% | 31.3% | |
| Lane Change | 10.8% | -15.0% | -15.1% |
| Slalom | 16.7% | 47.2% | 6.8% |
| J-Tum | | | |
| • Left | 23.1% | | 27.7% |
| • Right | 30.0% | 51.0% | |
| J-Tum w/Brake | | | |
| • Left | 10.7% | | 8.6% |
| • Right | 19.2% | 2.4% | |

### H. Suspension System Cost, Installation and Maintenance

An estimate of materials cost and man-hours required for the retrofit were obtained from DTI, Inc. The cost of a complete truck set (consists of six DTI struts and the associated mounting hardware required for conversion) will vary based on the number of P-18s retrofitted and any increase in materials cost over time. Estimated man-hours required for retrofit (per DTI) range between 32-48 hours, with DTI providing initial technical guidance on the first retrofit. Three estimates were provided by DTI for each Truck Set based on the total number of trucks retrofitted:

- 6 Truck Sets $18,642
- 15 Truck Sets $16,503
- 30 Truck Sets $14,982

The Air Force currently has 194 P-18 vehicles in inventory and additional savings would be realized with the retrofit of addition vehicles (i.e. greater than 30 Truck Sets).

Maintenance on the DTI suspension system is minimal. The vehicle should be checked for the ride height on a regular basis and adjusted as necessary. Environments that present extreme temperature variations may require ride height adjustment semi-annually. The struts should also be checked for signs of leakage at regular intervals. The suspension system should last between 5-10 years with proper maintenance and under normal driving conditions.

This information is provided for the sole purpose of providing the reader with an approximate estimate of materials cost and installation time. Endorsement of DTI as the only source for the suspension system is not intended by the Air Force Research Laboratory and any other agency associated with this test series.

## VI. RECOMMENDATIONS

The following modifications are recommended in addition to retrofitting with the DTI suspension system:

1. **Speed Notification Device.** An audible (i.e. verbal) device or heads-up display on the windshield would relay the speed of the vehicle to the operator without taking attention away from the road.

2. **Governor.** A governor would limit the operating speed of the vehicle and prevent the operator from exceeding the stability limits. Because this vehicle is not a primary firefighting vehicle, a few seconds delay in arrival to the scene will not compromise the capabilities or responsiveness of the firefighters.

3. **Rollover Warning Device.** A device should be installed to warn the operator when the vehicle is approaching the roll angle or lateral force required for rollover or slide-out.

4. **Black Box.** A device similar to an aircraft black box would provide data on the status of the vehicle, as well as, information on the response of the driver throughout the duration of vehicle operation.

5. **Dual Tires on the Rear Axle.** The addition of dual tires on the rear axle of the P-18 would enhance and compliment the stability of the retrofitted vehicle by widening the wheelbase. Changes to the current configuration would include the modification of the tire rim and wheel mounting to accommodate the dual tires and purchase of new tires.

## VIII. REFERENCES


1. Society of Automotive Engineers Test Procedures

   SAE J857,SAE J670E,SAE J695,SAE J874,SAE J897, and SAE J1159

2. SAE Paper #930831 “An Investigation into Dynamic Measures of Vehicle Rollover Propensity”, Andrej G. Nalecs, Shengyu Lu, and Kenneth L. d’Entremont, University of Missouri

3. SAE Paper #930832 “Repeatability of the Tilt-Table Test Method”, C.B. Winkler, S. E. Bogard and K. E. Campbell, University of Michigan Transportation Research Institute

4. SAE Paper #930763 “The Influence of Lateral Load Transfer Distribution on Directional Response,” Chris L. Clover and James E. Bernard, Iowa State University

5. SAE Paper #930760 “A Computer Simulation Analysis of Safety Critical Maneuvers for Assessing Ground Vehicle Dynamic Stabilty,” R. Wade Allen and Theodore J. Rosenthal, System Technology, Inc.

6. SAE Paper #922426 “Roll Stability Performance of Heavy Vehicle Suspensions” C.B. Winkler, S.M.Karamihas and S.E. Bogard. University of Michigan Transportation Research Institute.

7. SAE Paper # 910234 “Characteristics Influencing Ground Vehicle Lateral/Directional Dynamic Stability” R Wade Allen, Henry T Szokak, Theodore S. Rosenthal, David H. Klyde, and Keith Owens of Systems Technology Inc. Hawthorne, California.

## APPENDIX A
## VELOCITY, ROLL FORCE AND ROLL ANGLE BEFORE AND AFTER SUSPENSION RETROFIT

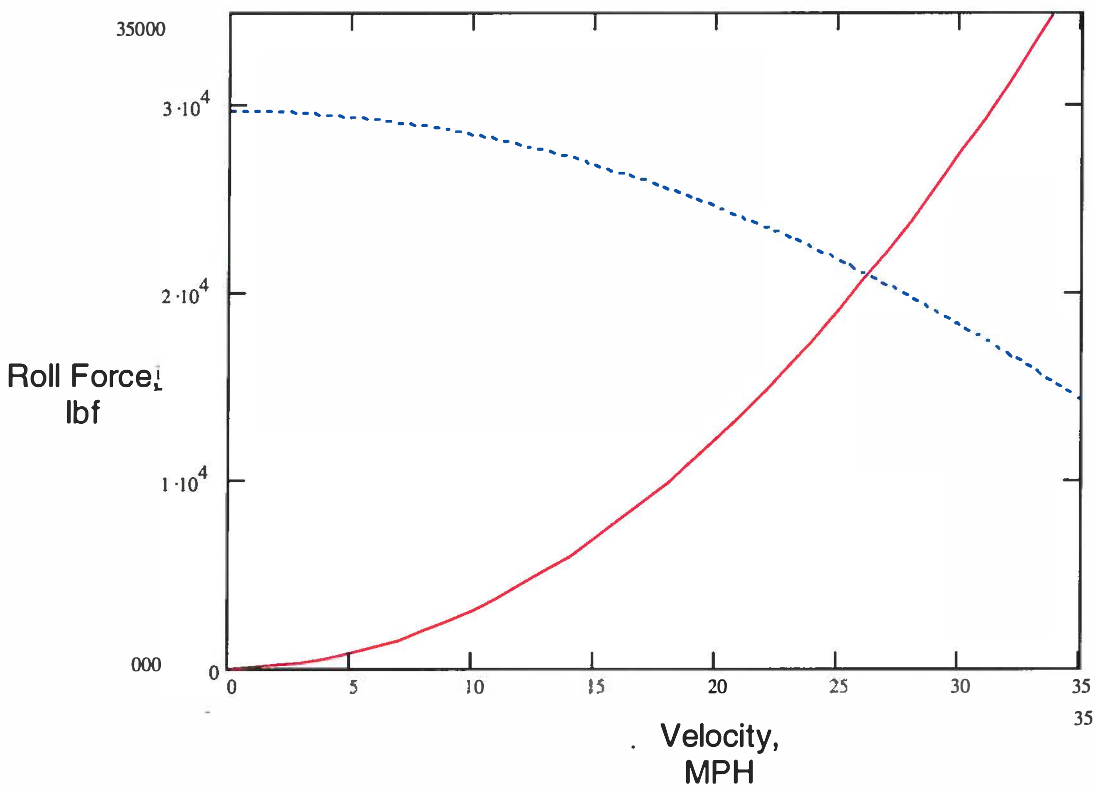


**Figure 26. Calculated Values for the Velocity and Roll Force Required to Roll the P-18, Original Configuration**

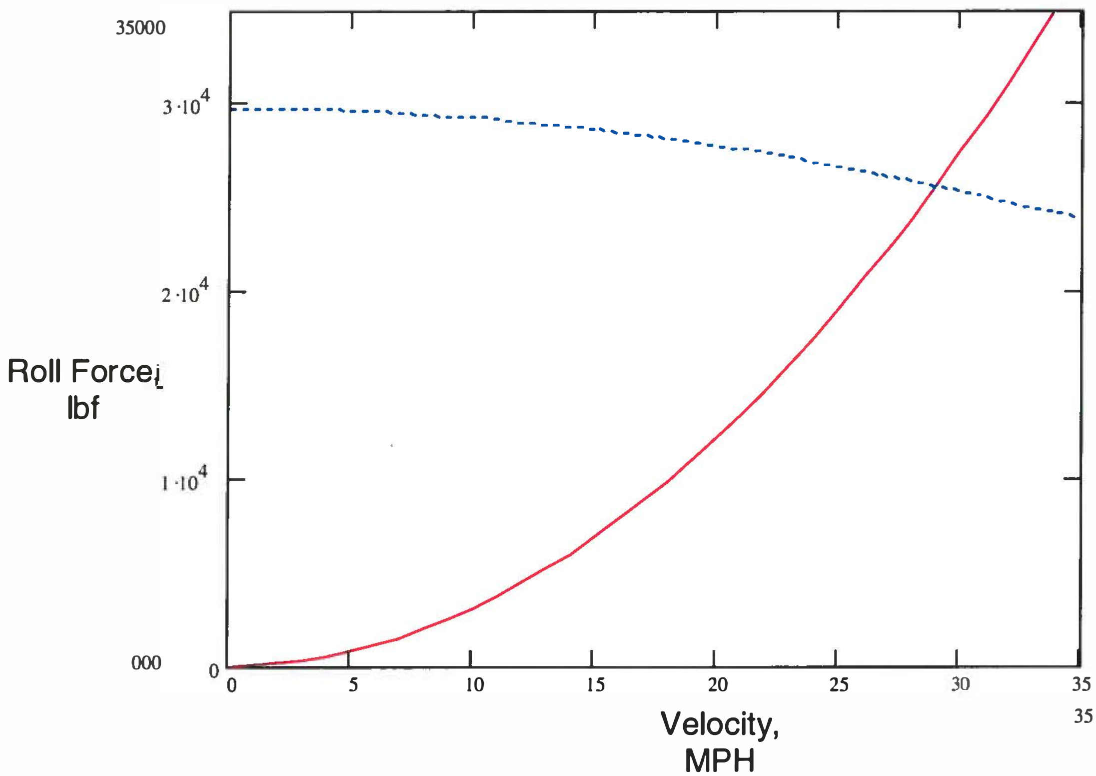


**Figure 27. Calculated Values for the Velocity and Roll Force Required to Roll the P-18, DTI Configuration**

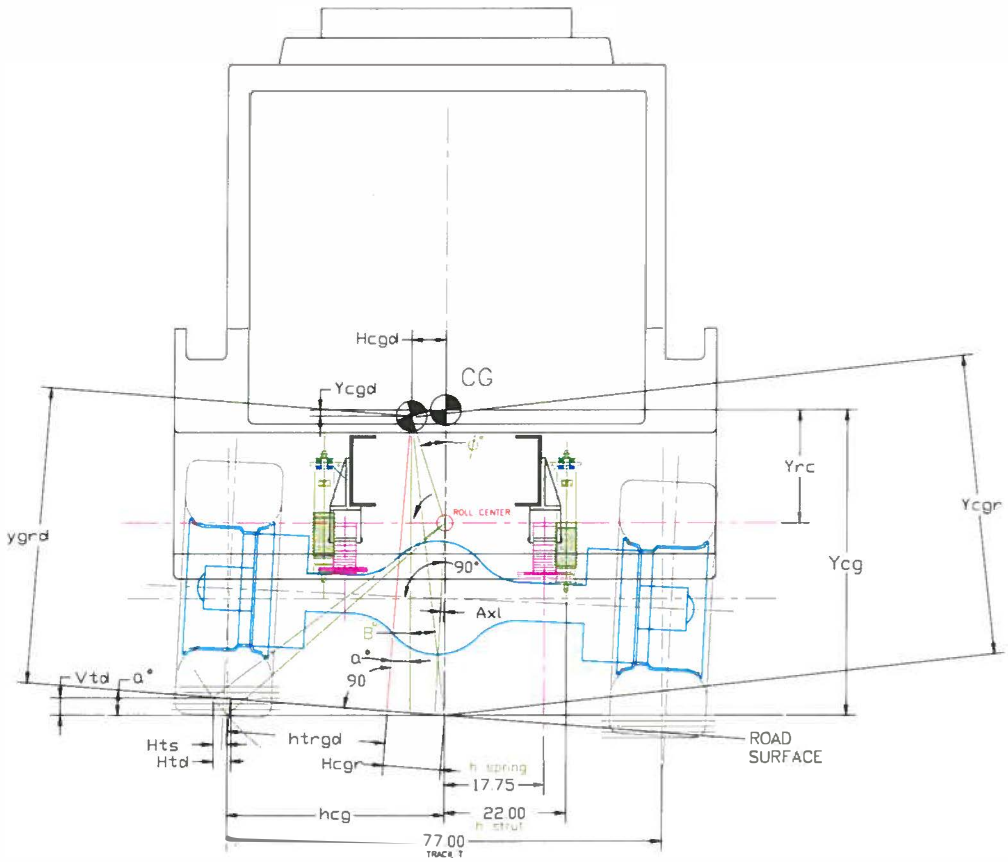


**Figure 28. Roll Angle with OEM Springs and DTI Suspension System**

# APPENDIX B
# DATA ACQUISITION TEST EQUIPMENT: PHASE I AND PHASE II

**Data acquisition software and hardware**
- DAQ Laptop (400 mhz pentium PII) and the signal junction box with 32 analog and 20 digital channels.
- Latest National Instruments data acquisition software and hardware boards

**Sensor position**

- Steering Transducer position
- Steering angle

**Front Axle to frame position**

- Vertical  position
- Left and right

**Mid rear axle spring to frame position**

- Vertical position
- Left and Right

**Mid axle to spring position**

- Vertical position
- Left and Right

**Accelerometers**

- Front axle at frame position
- Front lateral acceleration
- Left and Right

**Rear axle at frame position**

- Rear lateral acceleration
- Left and Right

**Laser Gyro at CG**

- Mounted on CG position inside the water tank
- Yaw rate
- Angle to test pad

## ACRONYMS

1. ARFF - Aircraft Rescue & Fire Fighting
2. AFRL - Air Force Research Laboratory
3. Cg - Center of Gravity
4. CNRC - Canadian National Resource Center
5. CTRC – Canadian Transport Research Center
6. DFW - Dallas/Fort Worth
7. DTI - Davis Technologies International, Inc
8. ERV - Emergency Response Vehicle
9. FAA - Federal Aviation Administration
10. G - Gravitational Constant
11. GVW - Gross Vehicle Weight
12. HPR - High Performance Rescue
13. MPH - Miles Per Hour
14. NFPA - National Fire Protection Association
15. OEM - Original Equipment Manufacturer
16. SAE - Society of Automotive Engineers